Innovation in Offshore Site Investigation

Gary Li (Fugro) & Dr. Vickie Kong (GEO)

Outline

1st – Gary Li (Fugro)

- **Background of nearshore and shallow site investigation**
- **Modern over-water investigation practice**
- **Free-fall technology development**
- **Evaluation of shear strength properties of seabed sediments**

2nd – Vickie Kong (GEO)

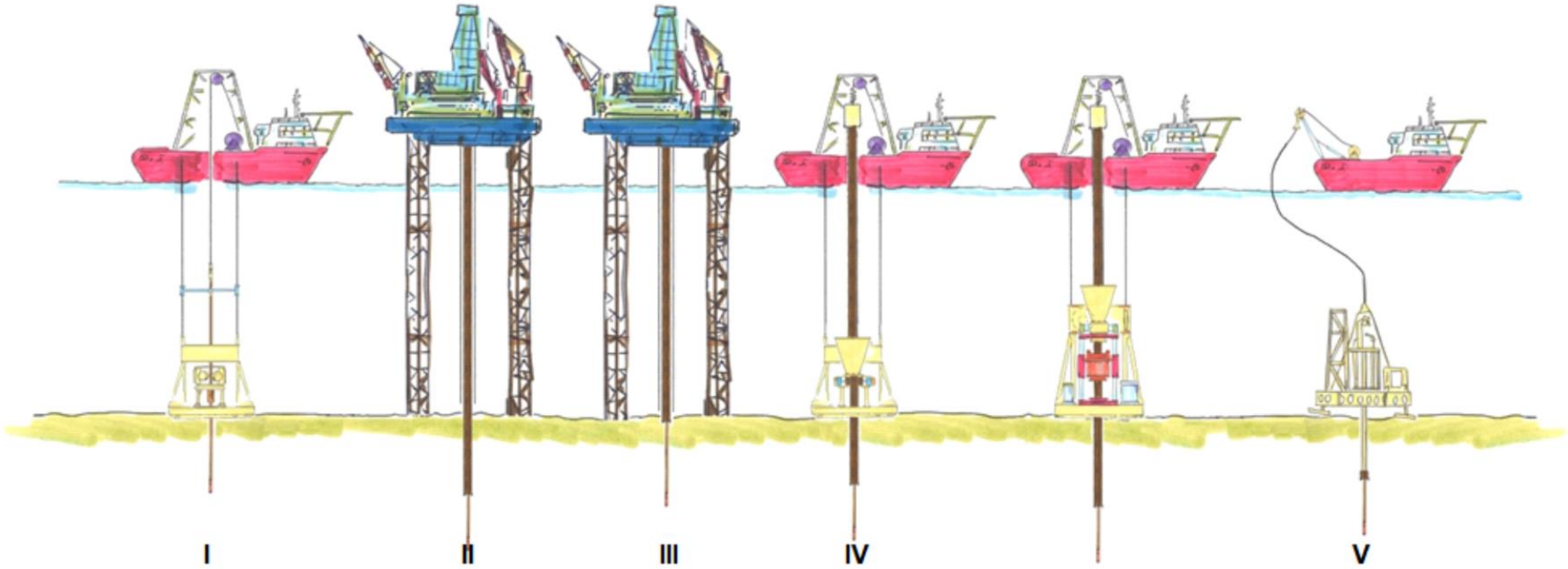
- **Development of novel site investigation tools**
- **Pipe-soil interaction**
- **Numerical modelling (LDFE) and centrifuge testing**
- **In-situ testing SMARTPIPE**

Background / Challenge of Marine SI

- **Challenging environment (both equipment and testing)**
- **Weather sensitive**
- **Distance away from land and water depth**
- **Improvement of traditional vessel-based drilling tools**
- **Development of technology to overcome challenging environment**
  - **Robotic seafloor system**
  - **Free-fall samplers and penetrometers**
- **Robustness data capture and data interpretation are crucial**
- **R&D to improve understanding of acquired data**

ISO 19901-8:2014 Marine Soil Investigations

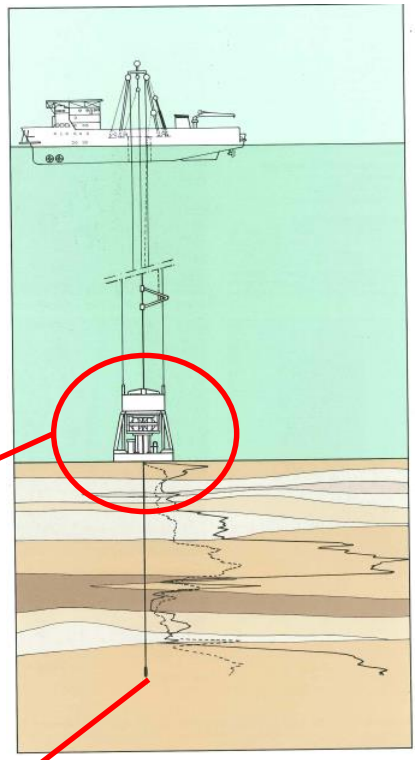
Deployment modes for marine soil investigation



Seabed Mode | Jack-up and permanent based structures | Downhole Mode | Hybrid Mode | Seafloor based

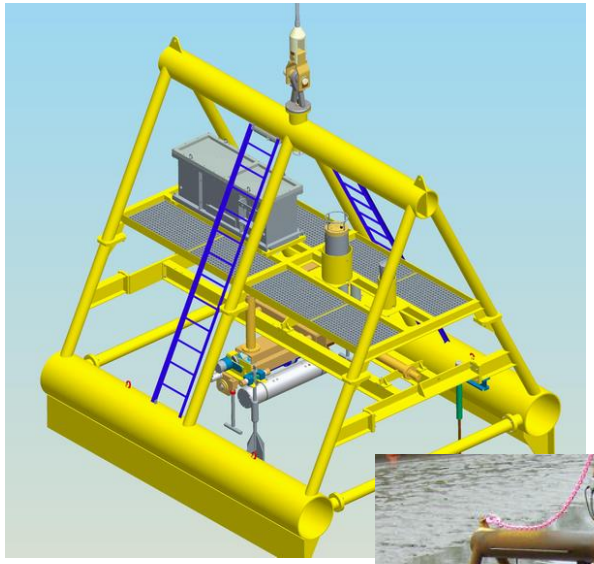
P Looijen and J Peuchen (2017) – Seabed Investigation by a Novel Hybrid of Vessel-based and Seafloor-based Drilling Techniques, International Conference of Offshore Site Investigation and Geotechnics, Society for Underwater Technology, London

Type 1 - Seabed Mode



Type 1 - Seabed Mode

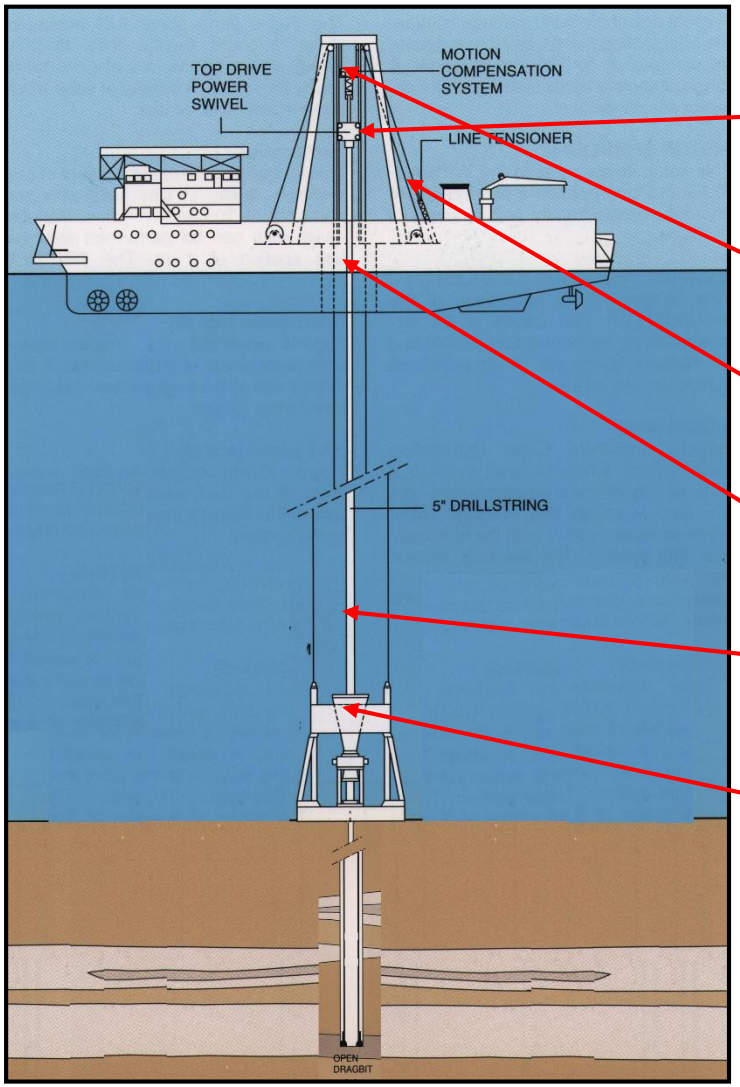
Shallow seabed penetrometer testing



Fugro's SmartSurf module for shallow sampling and penetrometer tests

Randolph, M.F. (2016) – New tools and directions in offshore site investigation, Geotechnical and Geophysical Site Characterisation 5 – Lehane, Acosta-Martinez & Kelly (Eds), 2016, Australia Geomechanics Society, Sydney, Australia

Types 2 - 4 – Jack-up and Vessel Drilling Modes



Top drive power swivel

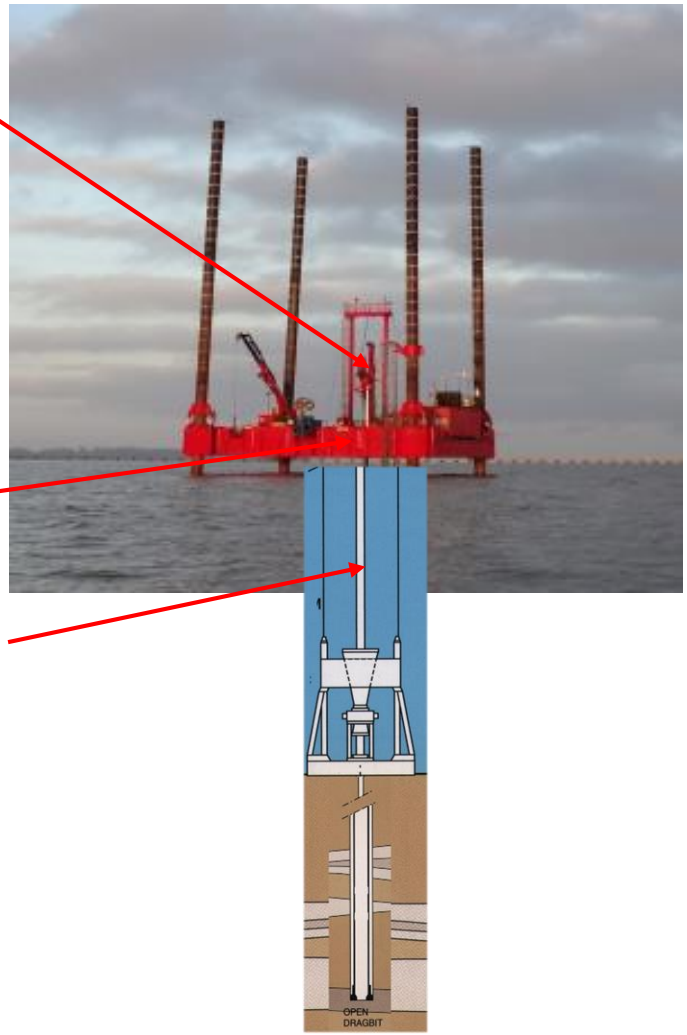
Motion compensator

Line tensioner

Moonpool

5” API drill string

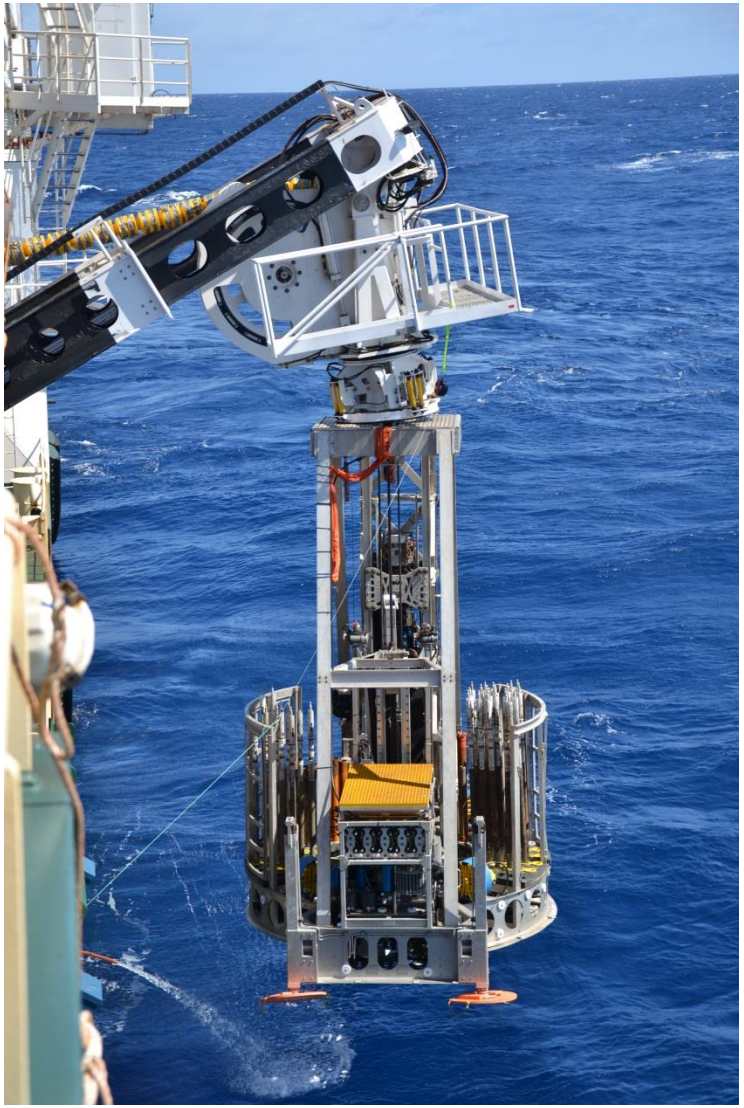
Seabed reaction/re-entry frame



Type 4 - Downhole mode

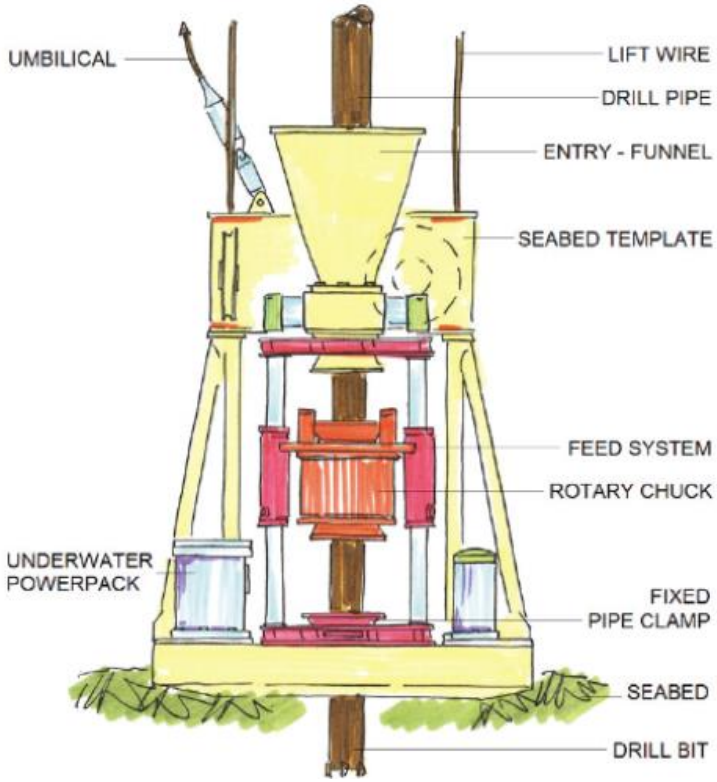
Type 5 – Seafloor based drilling

- **Water depth : 150 - 4,000 m**
- **Maximum penetration depth: 150 m bsf**
- **Drilling and sampling of 73 mm diameter sample**
- **Wireline CPT and vane**



Offshore Innovative Development – (between Types 4 & 5)

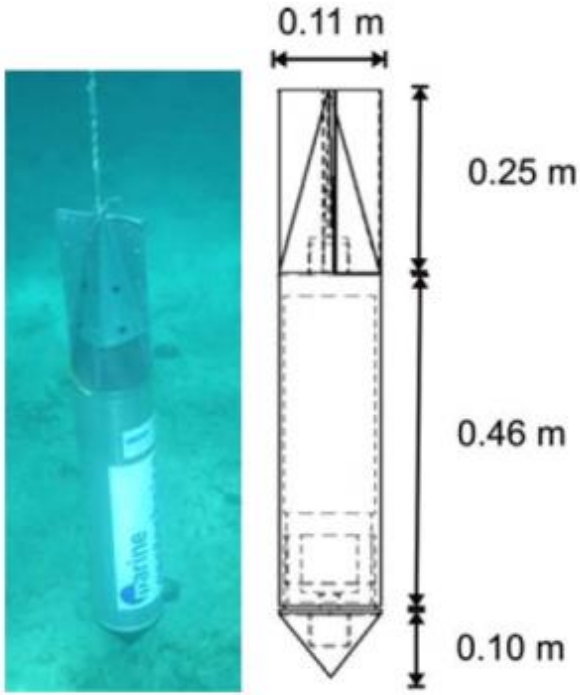
Hybrid Seabed Frame – Fugro Seadevil ™

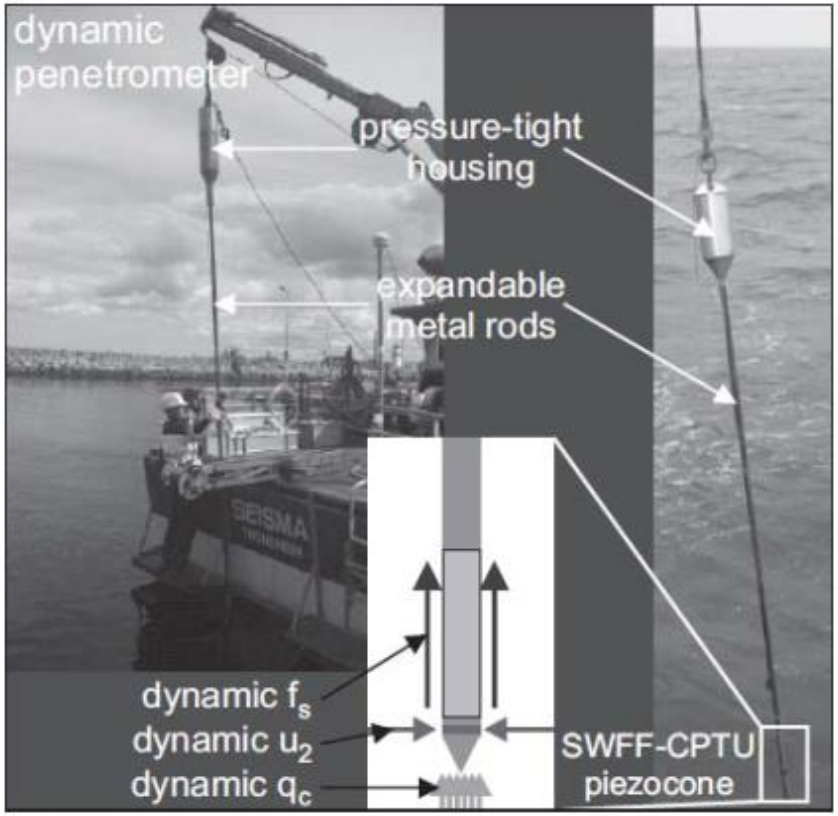


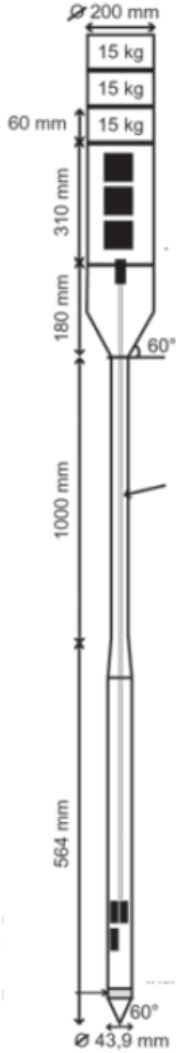
- Vessel-based or seabed drilling (using rotary actuator)
  - drill pipe connected to vessel through heave compensator; full suite of downhole tool available
- Alternative sample / CPT pushed from seabed frame

P Looijen and J Peuchen (2017) – Seabed Investigation by a Novel Hybrid of Vessel-based and Seafloor-based Drilling Techniques, International Conference of Offshore Site Investigation and Geotechnics, Society for Underwater Technology, London

Free Fall Penetrometer





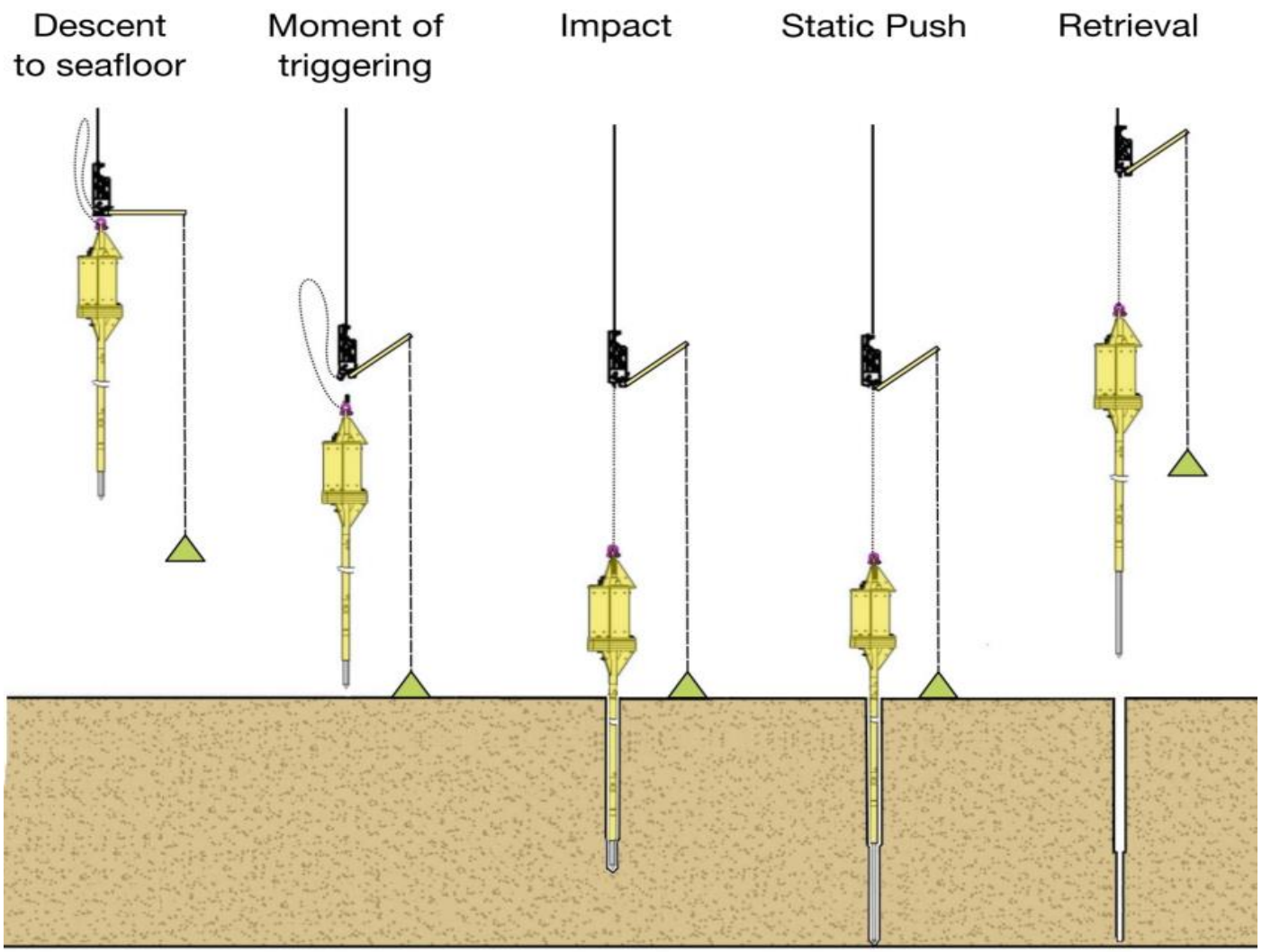


Combined dynamic and static penetration testing

- Fugro Seadart: free-falling device containing jackable cone penetrometer
- Cone protrudes during free-fall, is then penetrated further under static control

J Peuchen, P Looijen and N Stark (2017) – Offshore Characterisation of Extremely Soft Sediments by Free Fall Penetrometer, International Conference of Offshore Site Investigation and Geotechnics, Society for Underwater Technology, London

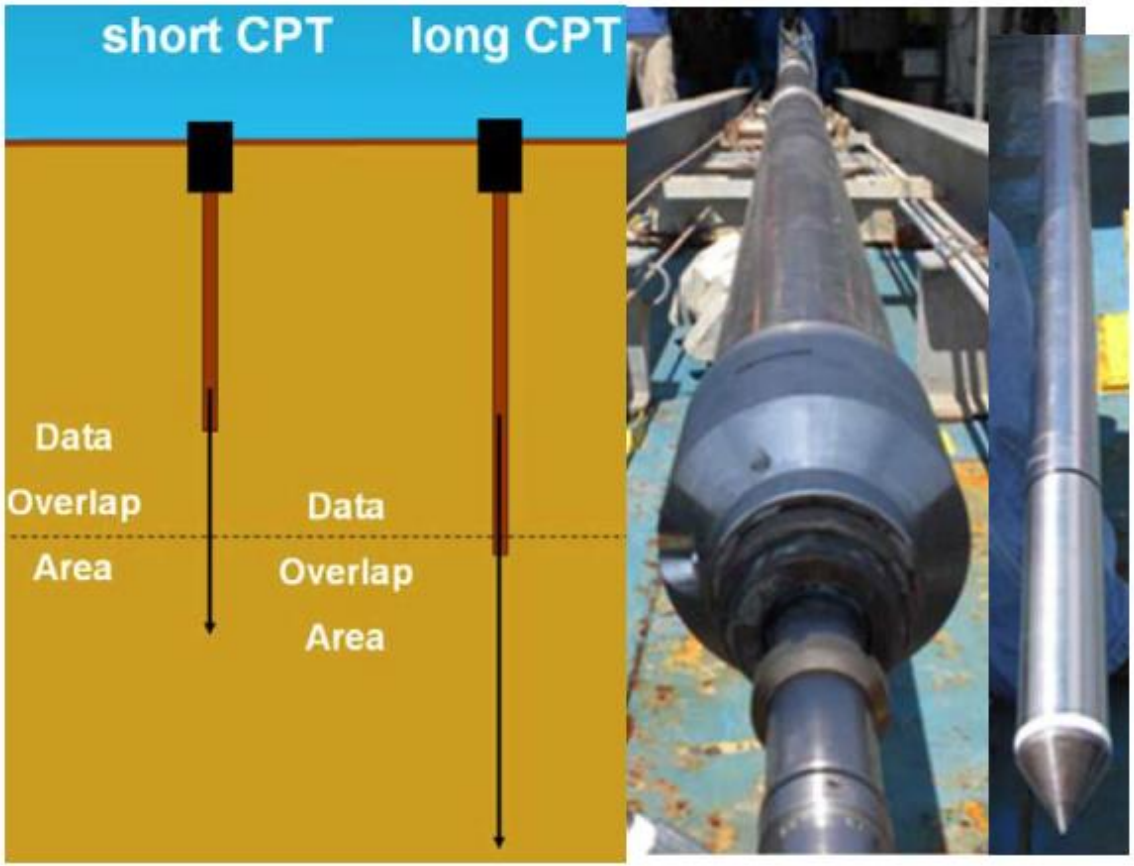
Combined dynamic and static penetration testing

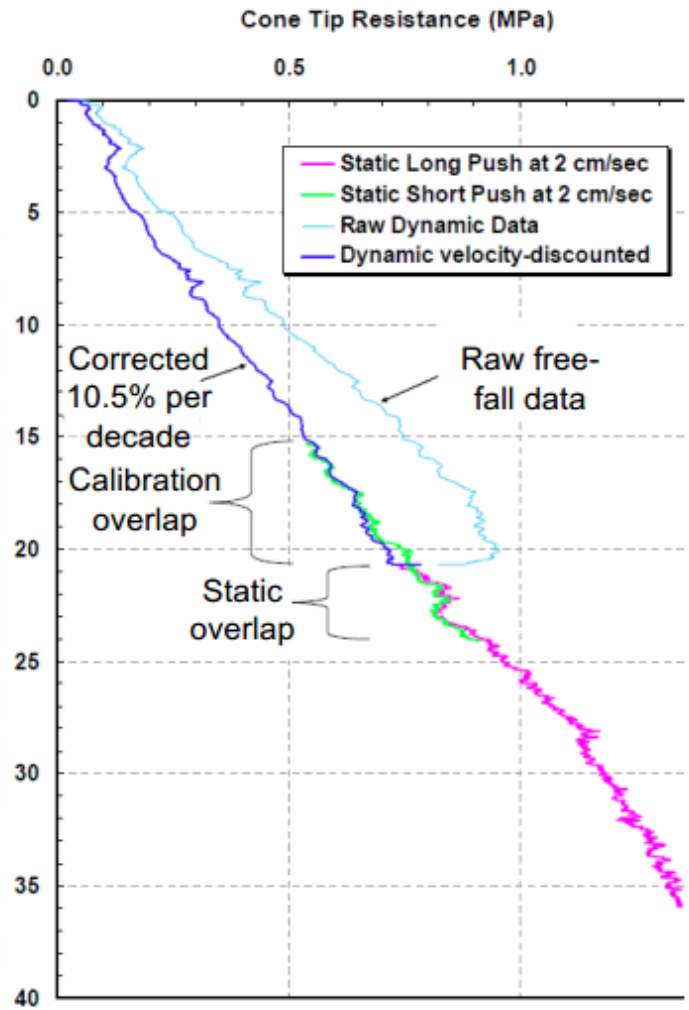



AM GE

Free Fall Penetrometer

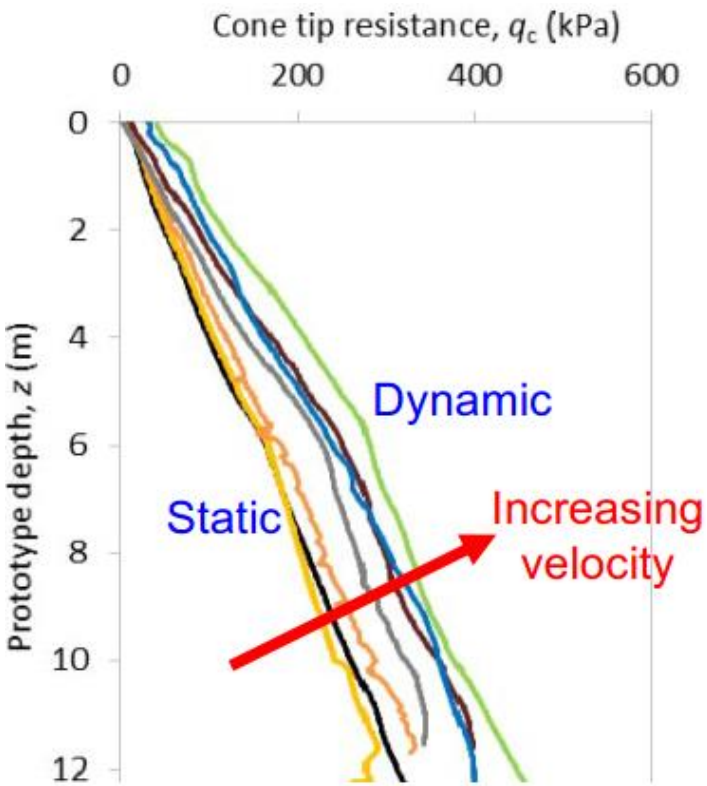
CPT – Stinger
(Young et al 2011 – TDI-Brooks)

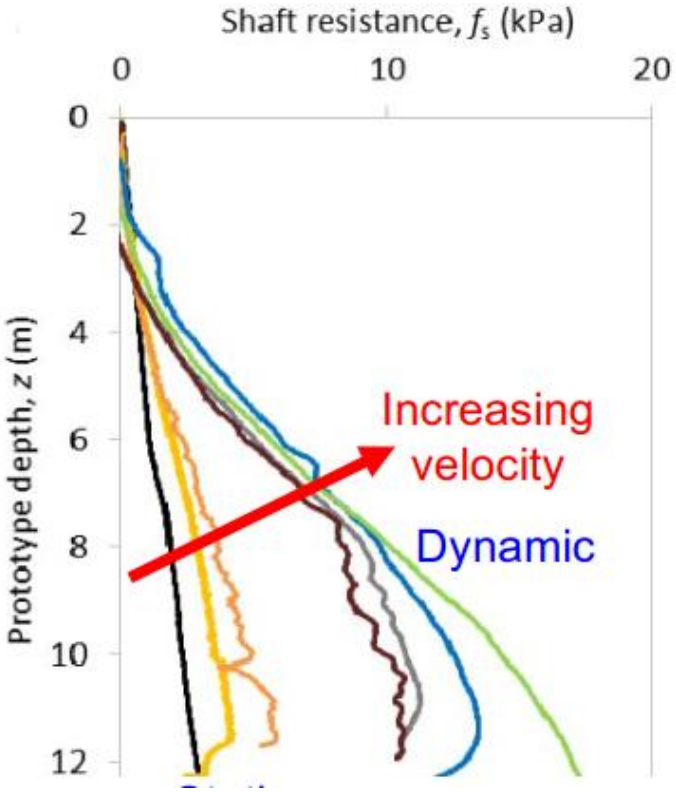




Young, A.G., Bernard, B.B., Remmes, B.D., Babb, L.V. and Brooks, J.M. (2011). "CPT Stinger" – an innovative method to obtain CPT data. Proc. Offshore Technology Conf., Houston, USA. Paper OTC21569.

Free Fall Penetrometers – Centrifuge Model Testing



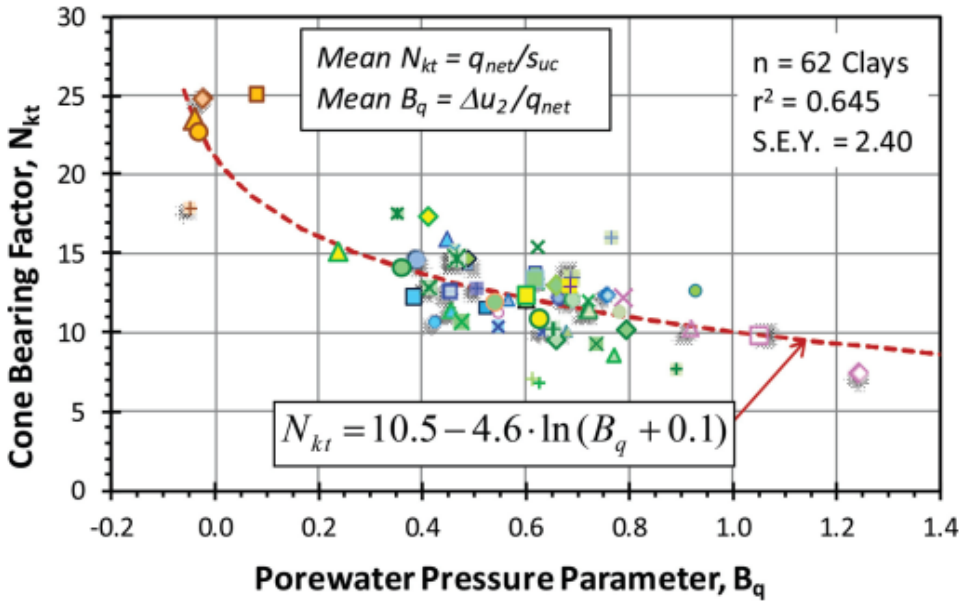


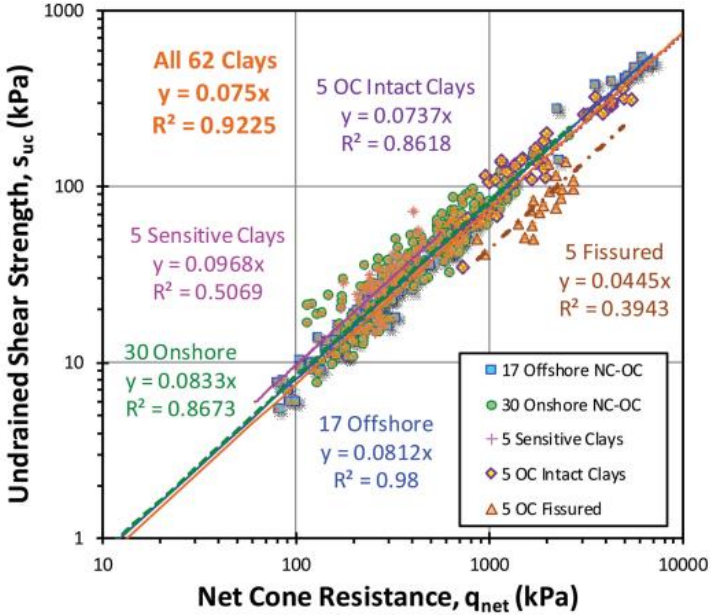
- Dynamic tip resistance 30 to 50% greater than static resistance
- Difference increase with increasing impact velocity at seabed
- Sleeve friction is more complex, with higher differences between dynamic and static
- RIGSS (Remote Intelligent Geot. Seabed Survey) JIP is currently underway at UWA

Chow, S.H., O'Loughlin, C.D., White, D.J. & Randolph, M.F. 2017. An extended interpretation of the free-fall piezocone test in clay. Géotechnique, 67(12): 1090–1103.

Evaluating shear strength properties

Mayne and Peuchen (2018) – Evaluation of CPT N_{kt} cone factor for undrained strength of clays





Clay Group	No. sites N	No. data n	Statistical Regressions Slope m	Coef.[a] r^2	Factor = 1/m N_{kt}	Mean B_q
Offshore NC-LOC	17	115	0.0812	0.980	12.32	0.51
Onshore NC-LOC	30	191	0.0833	0.867	12.00	0.53
Sensitive NC-LOC[b]	5	43	0.0968	0.507	10.33	0.84
OC Intact	5	36	0.0737	0.862	13.57	0.49
OC Fissured[c]	5	22	0.0445	0.393	22.47	–0.01
All Clays	62	407	0.0750	0.923	13.33	0.55

Mayne, P.W. & Peuchen, J. (2018) – Evaluation of CPTU N_{kt} cone factor for undrained strength of clays, Cone Penetration Testing 2018 – Hicks, Pisano & Peuchen (Eds), Delft University of Technology, the Netherlands

Evaluating shear strength properties

Summary from past studies

- Lunne et al (2005) – recommended $N_{kt} = 12$
- Low et al (2010) – $8.6 \leq N_{kt} \leq 15.3$ (average 11.9) for offshore clay
- Mayne et al (2010) – recommended $N_{kt} = 11.8$ for soft to firm clay
- Low et al (2010) – recommended $N_{kt} = 13.6$ (different shearing modes, $10.6 \leq N_{kt} \leq 17.4$)
- Low et al (2010) – reported $N_{kt} = 13.3$ (field vane shear with a range $10.8 \leq N_{kt} \leq 19.9$)
- Mayne and Peuchen (2018) – $N_{kt} = 10.3 – 22.5$ (for various soil types)

$$N_{kt} = 10.5 – 4.6 \times \ln(B_q + 0.1)$$

- Wang et al (2015) – reported an $N_{kt} = 10.5$ with VST

Author recommendations

- Cone factor, N_{kt} can be corelated with theoretical, experimental and statistical relationship
- Obtaining site specific correlation requires selective laboratory testing on high quality samples and field vane shear test
- Good understanding of the effects of sample disturbance
- Database and experiences are highly valuable for assessing N_{kt}

Innovation in Offshore Site Investigation

Vickie KONG

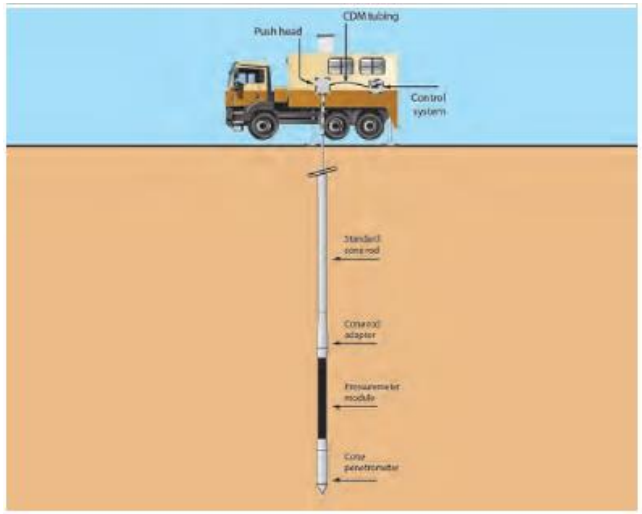
Introduction

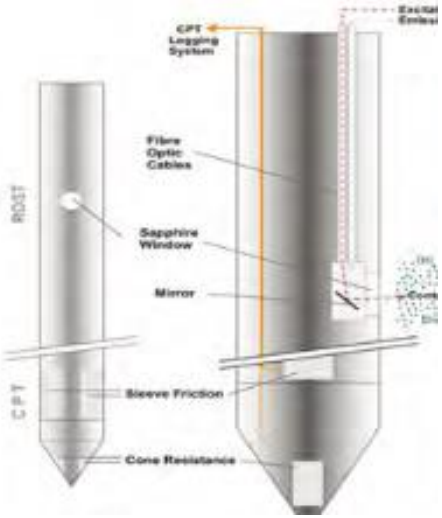
- Development of Novel Site Investigation Tools for Offshore Geotechnical Problems

- Soil Characterization
  - CPT
  - Alternative to CPT
- Pipe-Soil Interaction
  - Numerical modelling (LDFE)
  - Centrifuge Testing
  - In-situ testing SMARTPIPE

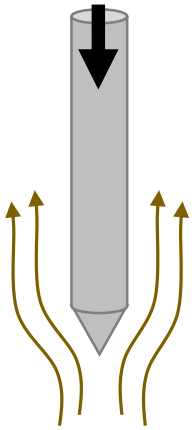
Penetration Test

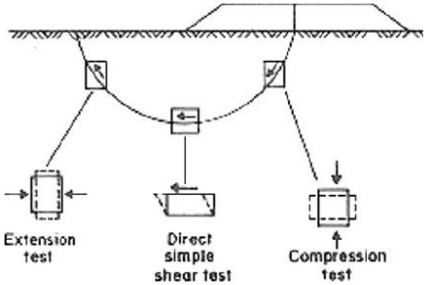
- CPT
  - Specification (36 mm Dia. , 60 deg tip)
  - Penetration at 20mm/s
  - q_c, u, f_s → soil characterisation





Evaluation of soil strength





$$s_u = \frac{\overbrace{q_c + u_2(1-\alpha) - \sigma_{v0}}^{q_{net}}}{N_{kt}}$$

Can be high in offshore environment!

Cone resistance affected by rigidity index, in-situ stress ratio etc. → *No exact solution*

Empirical Factor (back-calc. from laboratory testing)

Nkt = 10-20

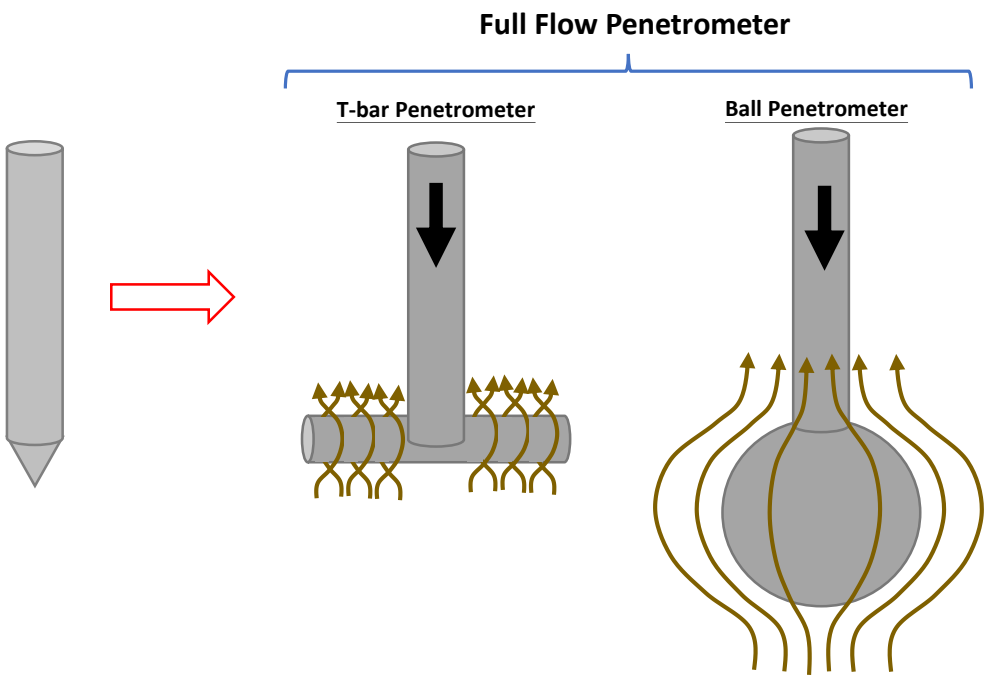
Failure Mode:

Similar to driving a pile!

But what about other failure modes?

Lunne, T., Andersen, K. H., Low, H. E., Randolph, M. F., & Sjursen, M. (2011). Guidelines for offshore in situ testing and interpretation in deepwater soft clays. *Canadian geotechnical journal*, *48*(4), 543-556.

Alternative to CPT

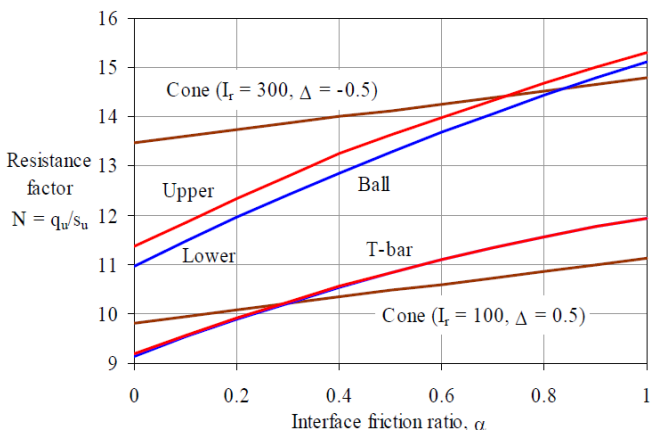


$$s_u = \frac{\overbrace{q_m - [\sigma_{v0} - u_0(1-\alpha)]A_s/A_p}^{q_{net}}}{N_{kt}}$$

Randolph, M., Cassidy, M., Gourvenec, S., & Erbrich, C. (2005, September). Challenges of offshore geotechnical engineering. In *Proceedings of the international conference on soil mechanics and geotechnical engineering* (Vol. 16, No. 1, p. 123). AA Balkema Publishers.

Full Flow Penetrometer

- Plasticity solutions, in a form of bearing capacity factor
  - Cylinder (1984)
  - Sphere (2000)
- Laboratory testing



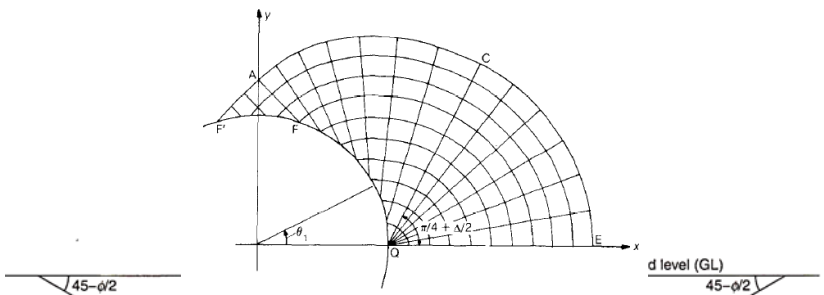


Fig. 3. Geometry of the characteristic mesh

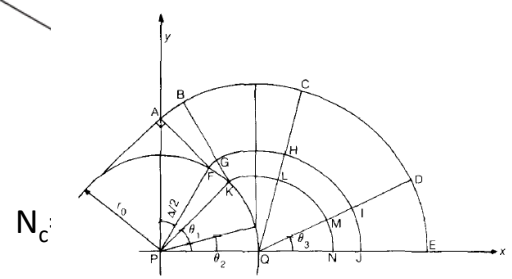


Fig. 4. Deformation mechanism

N_c … oil)

$q = N_{kt} \times S_u$

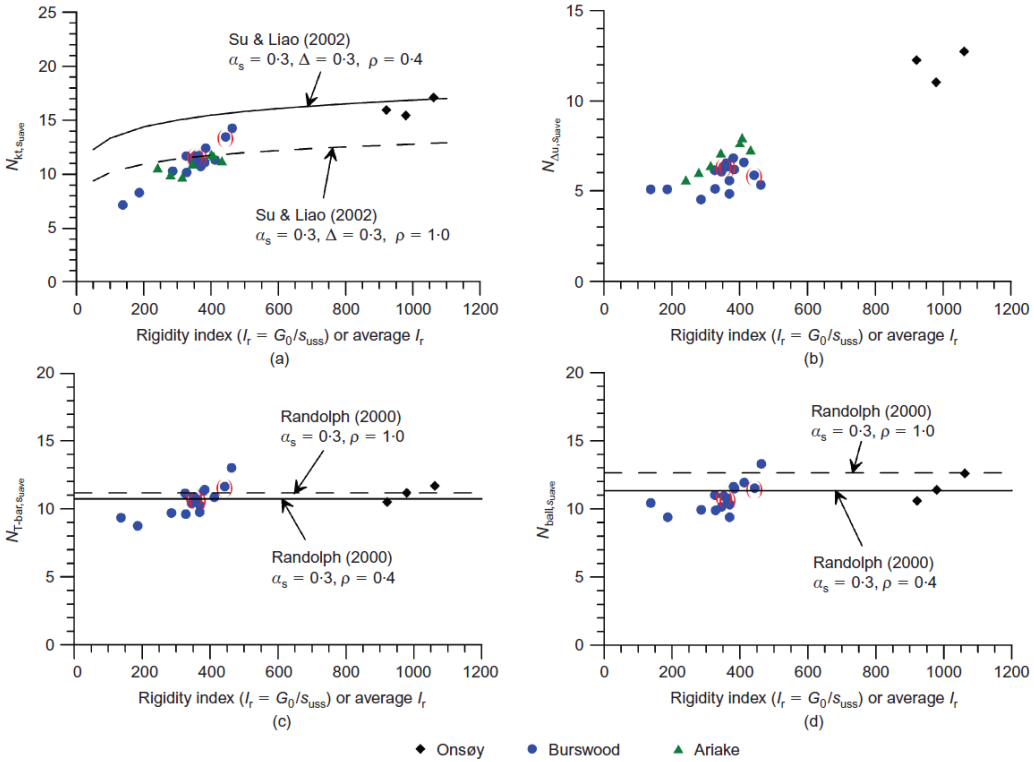
Randolph, M., Cassidy, M., Gourvenec, S., & Erbrich, C. (2005, September). Challenges of offshore geotechnical engineering. In *Proceedings of the international conference on soil mechanics and geotechnical engineering* (Vol. 16, No. 1, p. 123). AA Balkema Publishers.

http://www.soilmanagementindia.com/shallow-foundation/bearing-capacity-of-soil/bearing-capacity-of-the-soil-7-theories-soil-engineering/14439

Full Flow Penetrometer conti.

- Published data showed that the cone N_{kt} (= q_{net}/s_u) and $N\Delta u$ (= $(u_2 - u_0)/s_u$) factors are influenced by the rigidity index ($I_r = G/s_u$) of the soil.

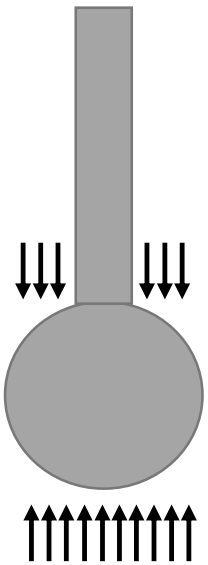
- In contrast, full-flow penetrometer $N_{T\text{-}bar}$ (= $q_{T\text{-}bar}/s_u$) and N_{ball} (= q_{ball}/s_u) factors are less dependent on secondary soil characteristics, apart from a slight effect of strength anisotropy (for soil with a strength sensitivity ≤ 8).



Low, H. E., Lunne, T., Andersen, K. H., Sjursen, M. A., Li, X., & Randolph, M. F. (2010). Estimation of intact and remoulded undrained shear strengths from penetration tests in soft clays. *Géotechnique*, *60*(11), 843.

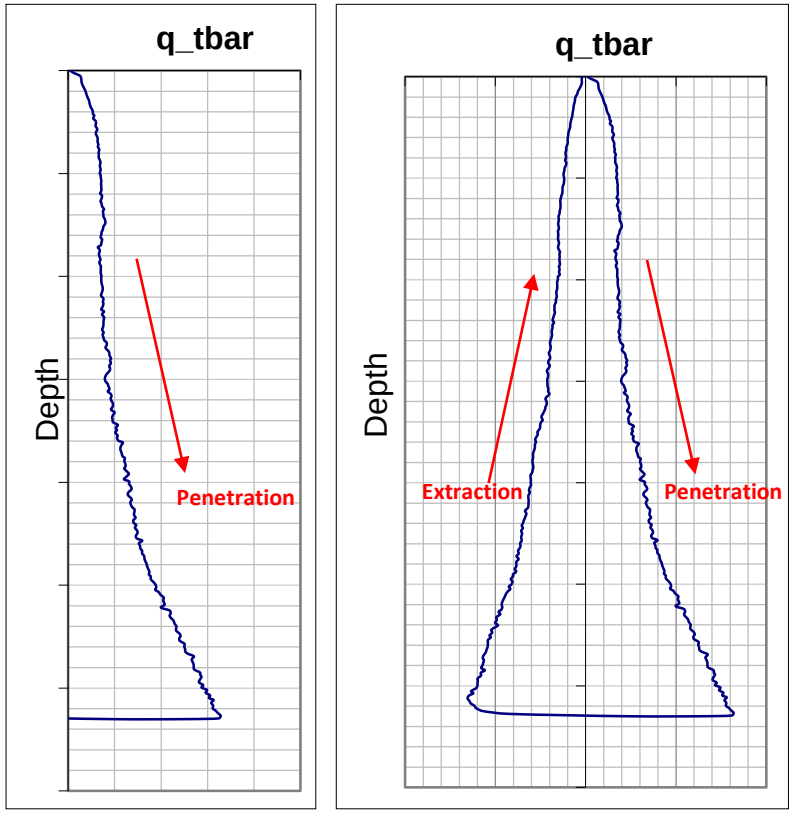
Full Flow Penetrometer conti.

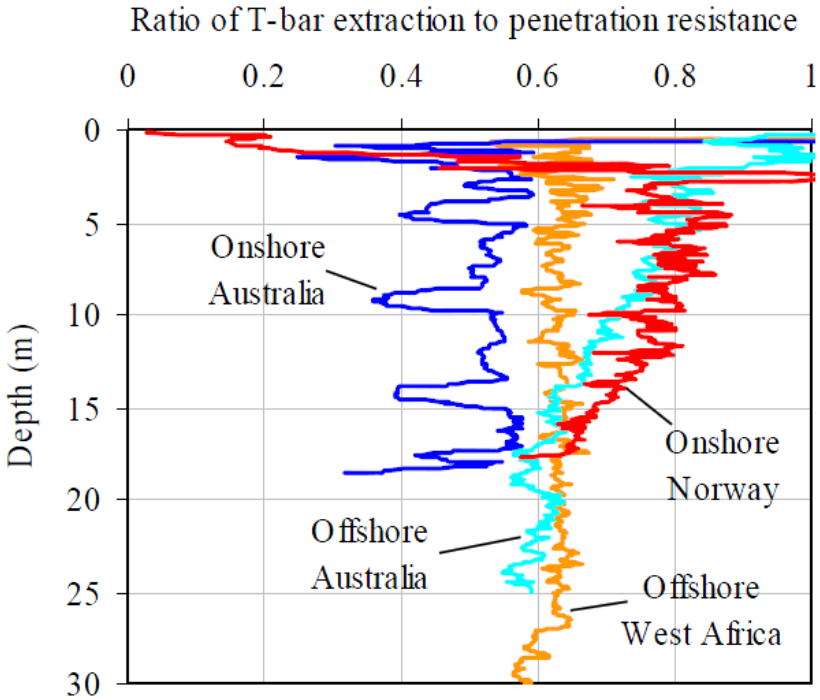
- Frontal Area =10 x Shaft Area
- Resolution - better measurement of soft clay (either onshore or offshore)



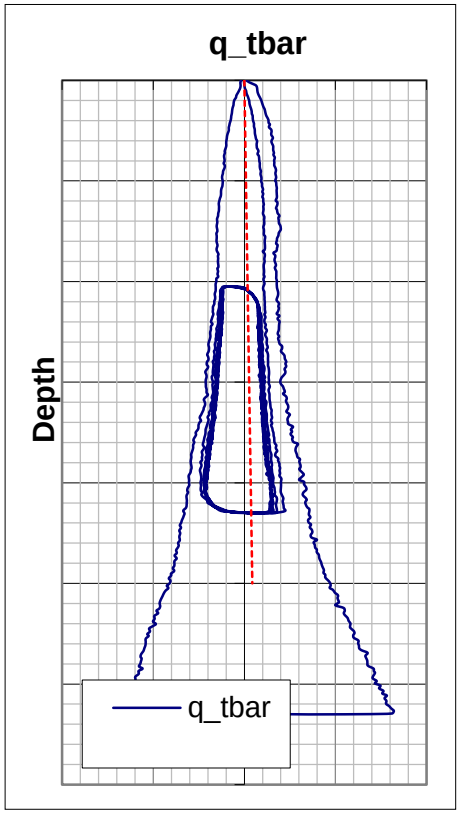
$$s_u = \frac{\overbrace{q_{m-[\sigma_{v0}-u_0(1-\alpha)]A_s/A_p}}^{q_{net}}}{N_{kt}}$$

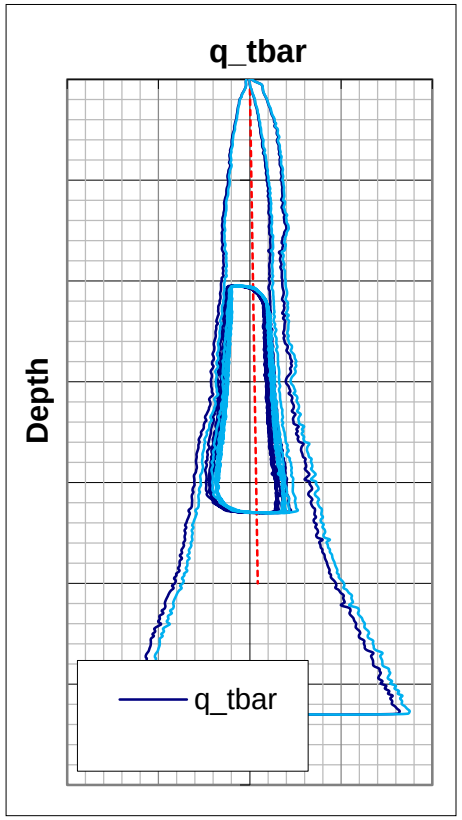
Full Flow Penetrometer conti.



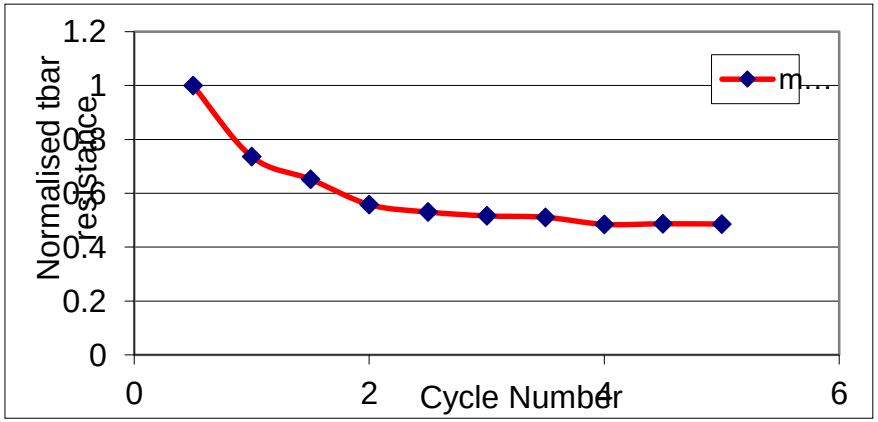


Full Flow Penetrometer conti.



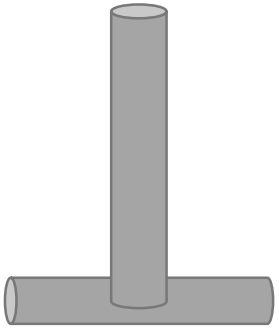


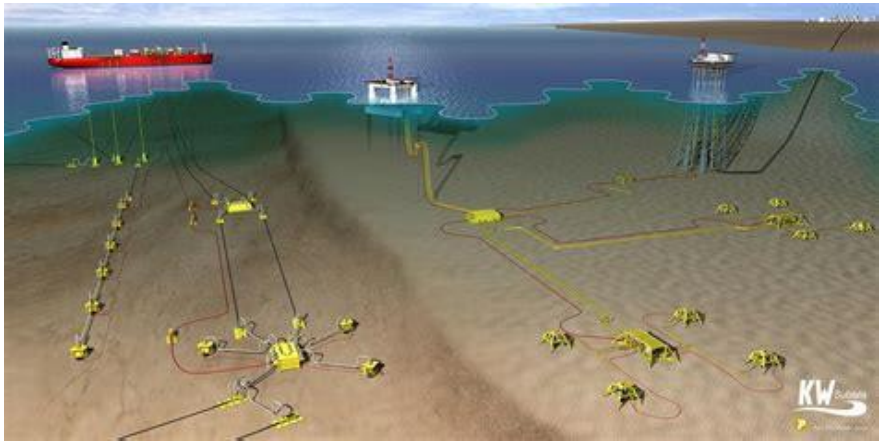
- Cyclic full flow penetration test
- Remoulded s_u, sensitivity
- Facilitate correction for error in zero load reading and error in net penetration resistance calculation



T-bar Penetrometer

- Developed for strength measurement in centrifuge sample
- First used in offshore environment in 1996
- Plane-strain condition

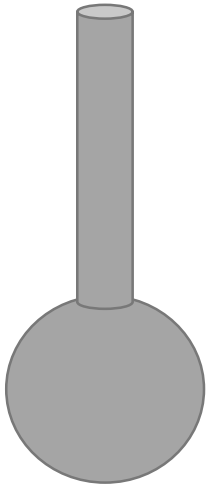




Randolph, M., Cassidy, M., Gourvenec, S., & Erbrich, C. (2005, September). Challenges of offshore geotechnical engineering. In *Proceedings of the international conference on soil mechanics and geotechnical engineering* (Vol. 16, No. 1, p. 123). AA Balkema Publishers.

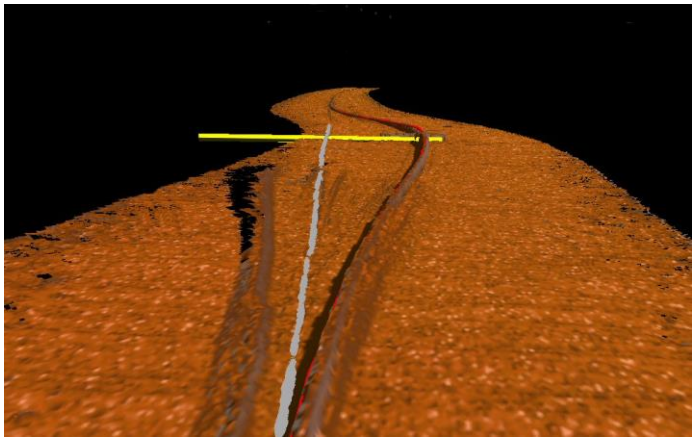
Ball Penetrometer

- First used in offshore environment in 2003
- Axisymmetric condition



Pipe-Soil Interaction

- Pipeline resting on seabed/inside trench
- Installation load, operation load (lateral, axial)
- Bearing failure, sliding failure
- ***Yes, it is a geotechnical problem!***



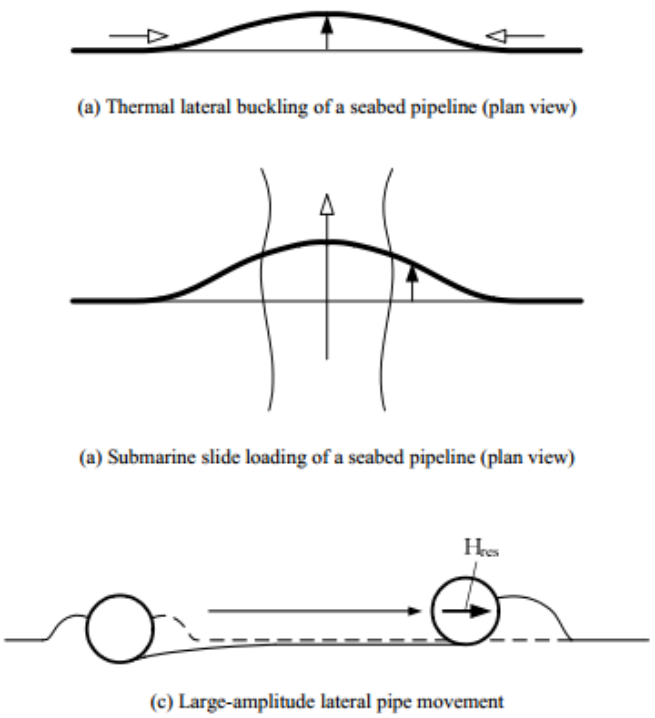
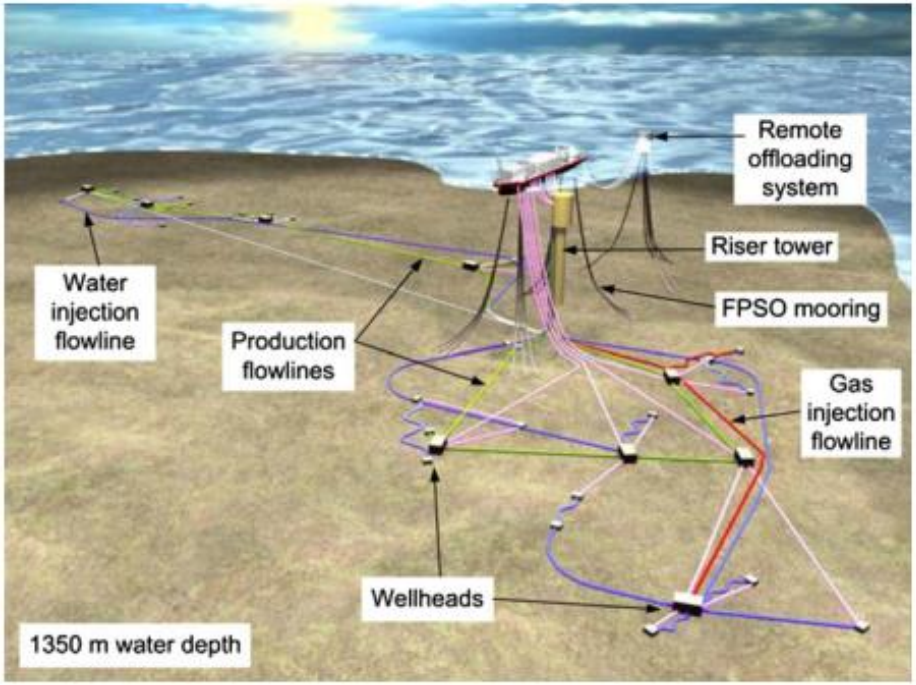


Figure 1 Problem definition

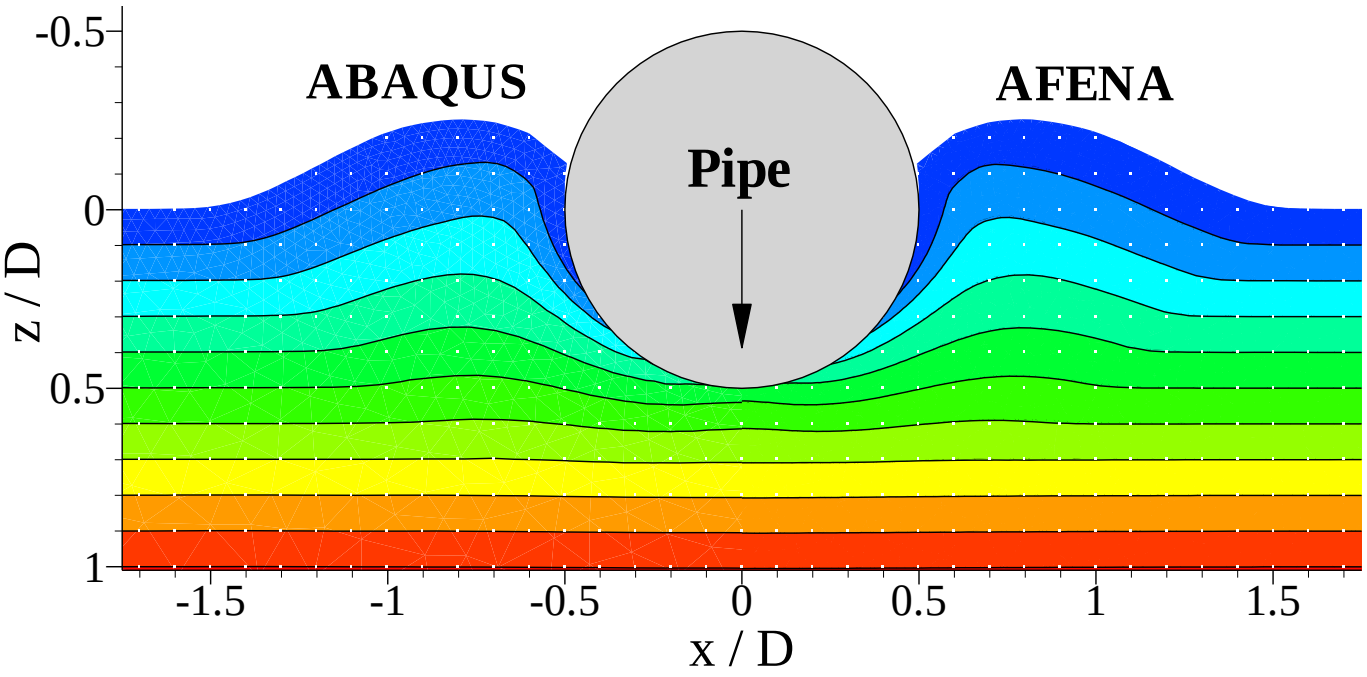
Pipe-Soil Interaction

- SAFEBUCK Joint Industry Project
- Numerical Modelling
  - Wish-in-place
  - LDFE
- Centrifuge Testing
  - Load test
  - PIV
- In-situ Testing
  - SMARTPIPE



Jayson, D., Delaporte, P., Alber,t J.-P., Prevost, M.E., Bruton, D., Sinclair, F., 2008. Greater Plutonio project—subsea flowline design and performance. In: Proceedings of the Conference on Offshore Pipeline Technology, OPT, Amsterdam

Pipe-Soil Interaction – Numerical Modelling



Lateral Buckling – LDFE

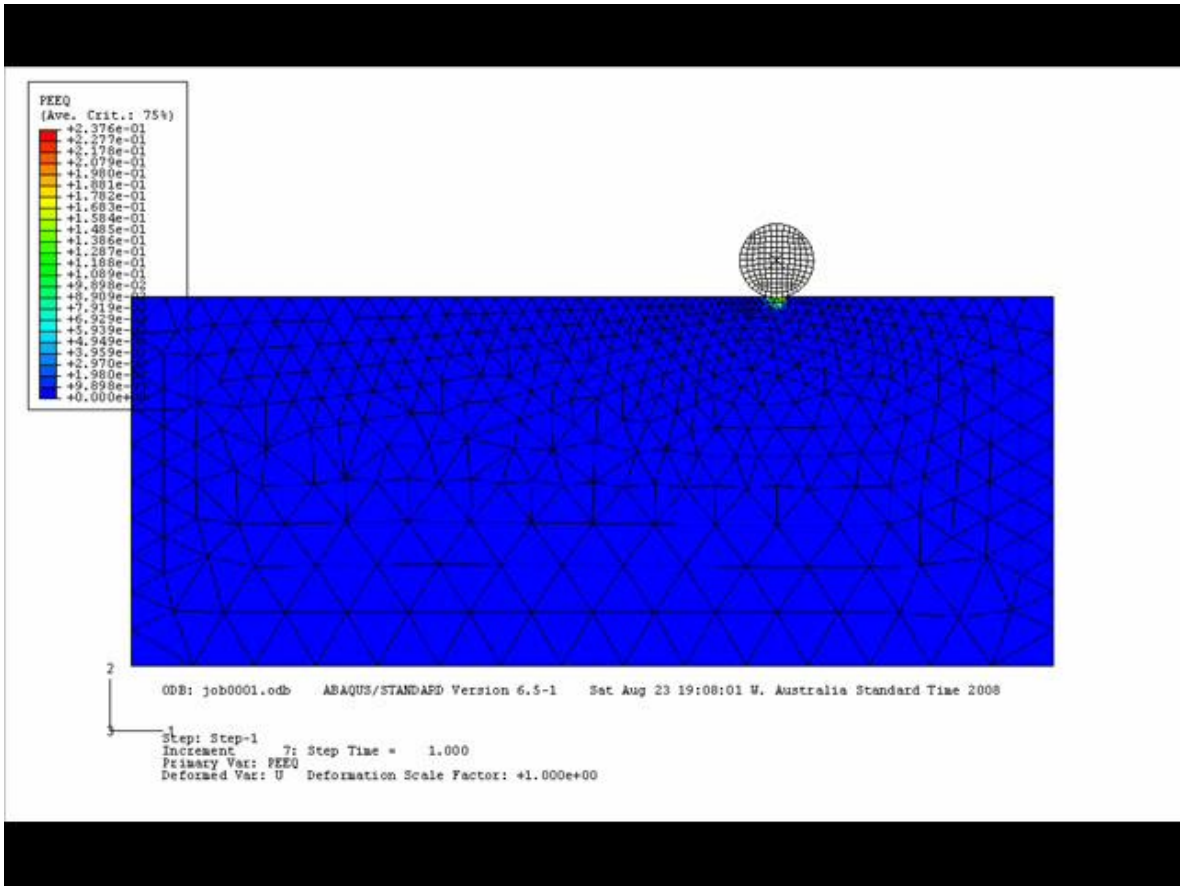


Fig. 7. Pipe embedment during lateral displacement (R = 5.26).

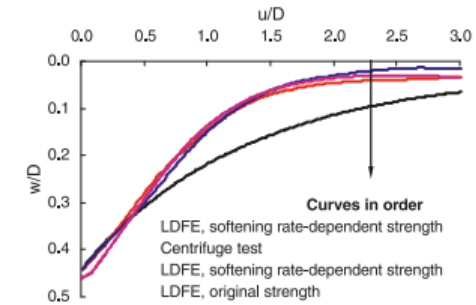
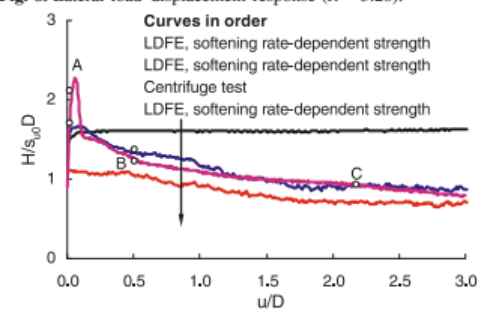


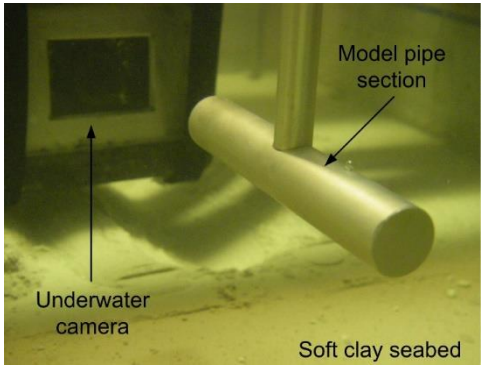
Fig. 8. Lateral load–displacement response (R = 5.26).

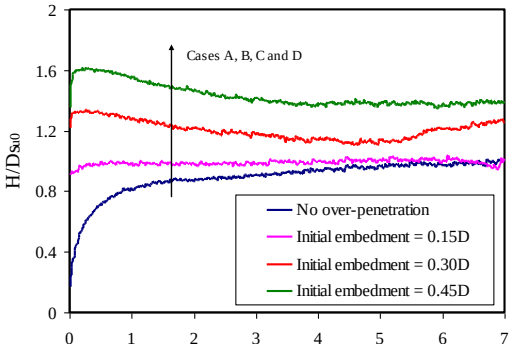


Wang, D., White, D. J., & Randolph, M. F. (2010). Large-deformation finite element analysis of pipe penetration and large-amplitude lateral displacement. *Canadian Geotechnical Journal*, *47*(8), 842-856.

Lateral Buckling - Centrifuge Test

- Model pipe
- Load-displacement relations based on reconstituted soil



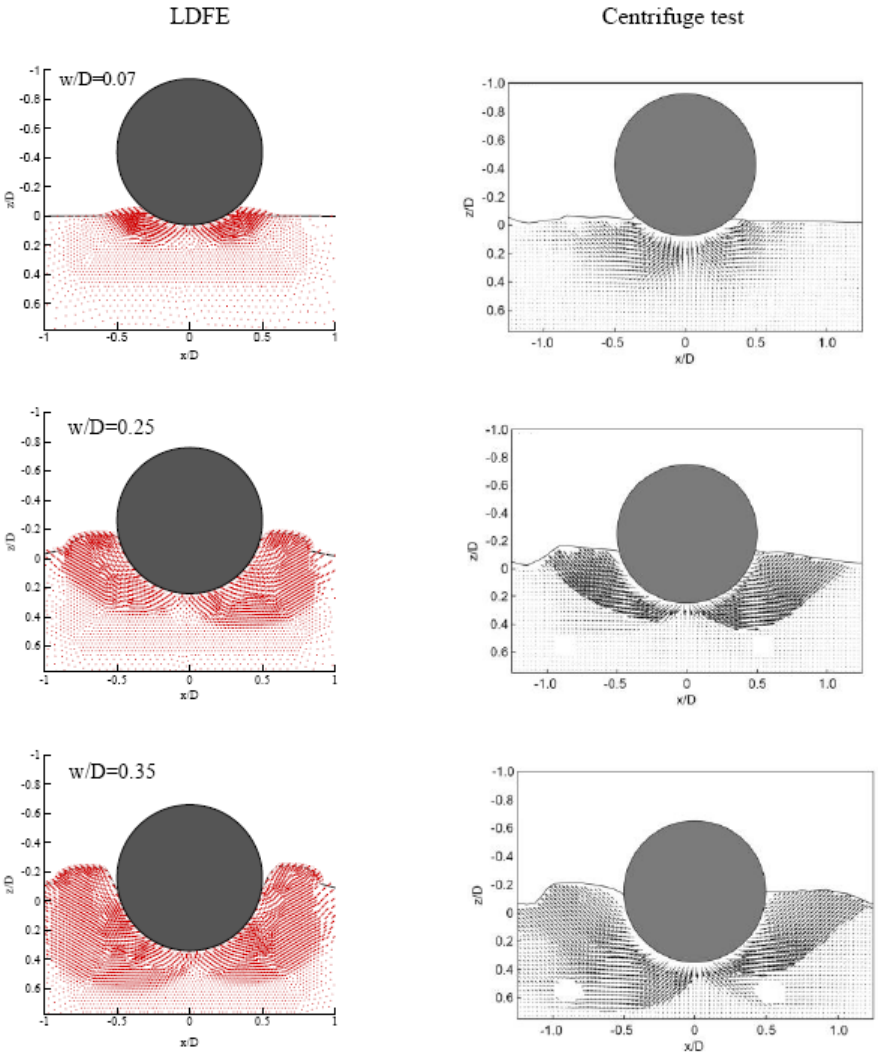


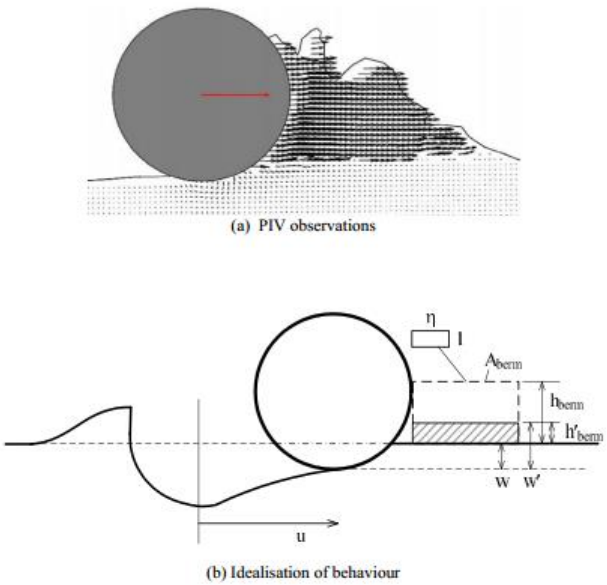
Lateral Buckling – PIV Test in Centrifuge

- Failure Mechanisms

Dingle, H. R. C., White, D. J., & Gaudin, C. (2008). Mechanisms of pipe embedment and lateral breakout on soft clay. *Canadian Geotechnical Journal*, *45*(5), 636-652.

Lateral Buckling – Failure Mechanism





(a) PIV observations

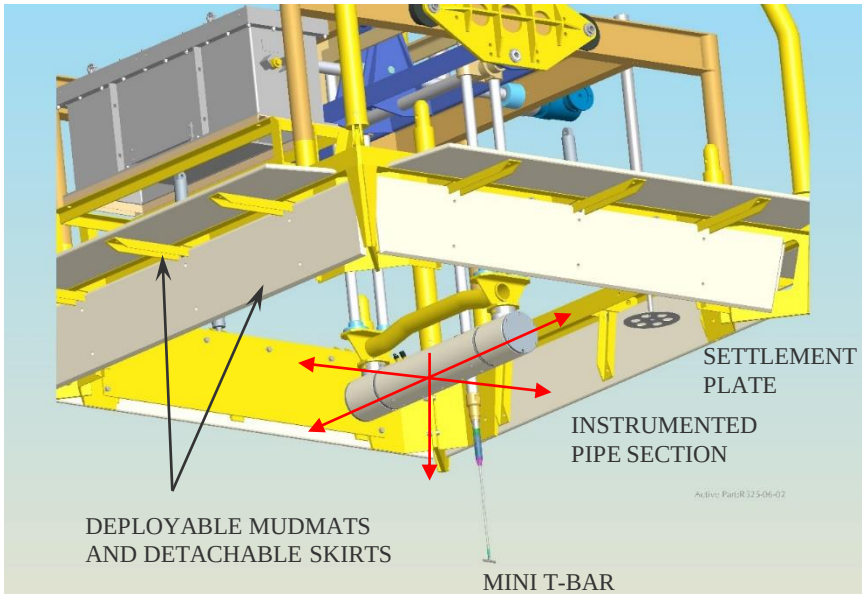
(b) Idealisation of behaviour

Figure 5 Berm sliding mechanism

SMARTPIPE

- **Jointly developed by BP, University of Cambridge and Fugro**
- **A newly developed instrument**

  - Section of model pipe (~225mm Dia)
  - PPT, LVDT, Inclinometer, T-bar, video
  - Static and cyclic axial and lateral load
  - Operate up to 2,500m water depth



White, D. J., Hill, A. J., Westgate, Z., & Ballard, J. C. (2010). Observations of pipe-soil response from the first deepwater deployment of the SMARTPIPE. In *Proc. 2nd Int. Symp. on Frontiers in Offshore Geotechnics, Perth* (pp. 851-856).

Hill, A. J., & Jacob, H. (2008, January). In-situ measurement of pipe-soil interaction in deep water. In *Offshore Technology Conference*. Offshore Technology Conference.

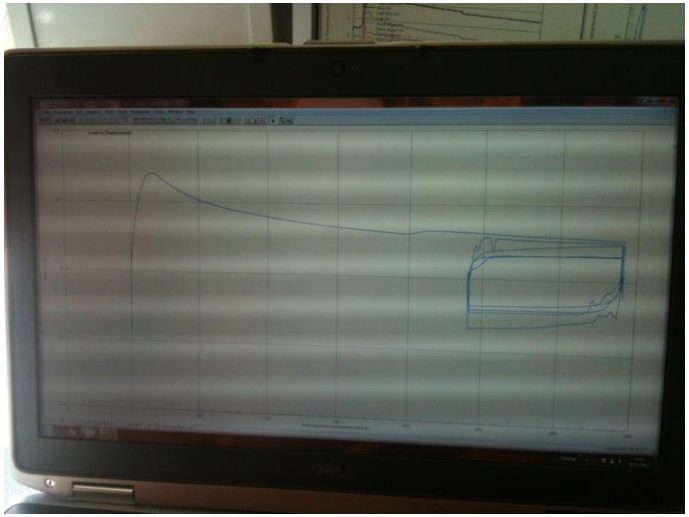
SMARTPIPE conti.

- “Large Scale” Model Test
- Part of Model Test (PIV centrifuge Test, Centrifuge Test, 1g Test)

Randolph, M. F., Gaudin, C., Gourvenec, S. M., White, D. J., Boylan, N., & Cassidy, M. J. (2011). Recent advances in offshore geotechnics for deep water oil and gas developments. *Ocean Engineering*, *38*(7), 818-834.

SMARTPIPE Campaign – site supervision

- Monitor the fundamental soil responses
- Cyclic T-bar test to obtain the soil profile and basic parameters



Mini T-bar
(1.5 m stroke)

My ‘colleagues’

Summary

- Development of Novel Site Investigation Tools
  - Theoretical basis
  - Industry-driven
- New problems
  - Opportunities for Geotechnical Engineers!

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Joek Peuchen – Fugro, The Netherlands

Peter Looijen – Fugro, The Netherlands

Thank you!